Developing a MIMO Test Methodology using Dynamic Channel Models and Link Adaptation

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***Abstract*—Industry standards for over-the-air testing of LTE MIMO devices have used multi-probe anechoic chamber based systems, also known as the boundary array method, to evaluate device performance in a spatially static environment. The spatial distribution of clusters in the chosen channel models, such as the SCME Urban Micro and Urban Macro channel models, are fixed, and the only geometric variation relative to the device under test is accomplished by physically rotating the device in the generated test environment. For 5G FR1 testing, 3GPP has adopted a similar approach. However, in an effort to meet the desire of the North American cellular network operators to better understand the behavior of a device on a realistic network, the CTIA MIMO OTA working group is developing a test plan based on the use of dynamic channel models that vary the spatial configuration as a function of time, and allowing the communication tester base station emulator to perform link adaptation, allowing the device to choose the best MIMO or SISO diversity mode and data rate for a given channel condition. This paper will discuss the design considerations associated with developing this new channel model and the related test system requirements.**

***Index Terms*—5G, MIMO, OTA, Testing, channel model**

I. INTRODUCTION

In the mid-2000s, when it became apparent that Wi-Fi and eventually cellular technologies would be adopting multiple-input multiple-output (MIMO) radio technologies to increase the available bandwidth, a system and method were developed to create a simulated RF environment that could potentially replicate any desired real-world channel condition given sufficient channel emulation resources[1]-[2]. Unlike conducted testing using channel emulators, which required embedding information or assumptions about the antennas to be used with the radio into the channel model, this boundary array method would create a near-field spatial environment that would contain all of the same complexity of a multipath environment that originated in the far field. Through the use of specially configured spatial channel models, the angle-of-arrival (AoA) information was transferred directly to the test volume through the boundary array of antennas. This allowed for evaluation of the over-the-air (OTA) performance of a device under test (DUT), including the impact of the physical design and placement of the MIMO antennas, without the need to modify the channel model to include that information in a conducted performance test.

This methodology was eventually standardized for LTE testing in both 3GPP and CTIA as the multi-probe anechoic chamber (MPAC) method (to distinguish it from reverberation chamber methodologies), and utilized the previously standardized SCME Urban Micro (UMi) and Urban Macro (UMa) models, respectively, with a particular base station antenna assumption. In the 3GPP scenario, the test involved measuring throughput vs. power to determine a receiver sensitivity based on the platform noise floor and self-interference. In the CTIA scenario, throughput was measured as a function of signal-to-interference ratio (SIR) as a spatially uniform AWGN interference was increased. This approach removed the impact of antenna gain and receiver sensitivity from the test and instead concentrated on the spatial correlation behavior of the antennas in the device. In both cases, the channel model exhibits a fixed directional behavior, requiring the rotation of the device within the created environment in order to determine its average performance in that scenario. Even then there was disagreement as to the best approach to determining the average performance from the individual measurements. In both cases, tests are performed in a fixed reference channel with the device forced into a Rank 2 open-loop MIMO configuration at a fixed modulation and coding scheme.

With the advent of 5G, for FR1 testing, 3GPP has proceeded down a path very similar to that used for LTE, simply updating the channel model and increasing the required number of probes to accommodate testing of antenna spacings larger than a wavelength [3]. Within CTIA, the carrier members have had a desire for some time now to investigate the use of a variable reference channel (VRC) that would allow the device to adapt to the channel in whatever manner it saw fit. There is an underlying belief that some devices, left to their own, may perform better in a SISO diversity mode than in full MIMO operation given a particular channel condition. When it came time to develop a MIMO OTA test solution for 5G, the proposal was made and accepted to not only investigate the use of the VRC to allow link adaptation, but to eliminate the static channel model in favor of one that more realistically represented the variability seen by the device in the real world. Such a “virtual drive testing” approach has been used by various manufacturers in the past to evaluate the behavior of their devices, but has never before been standardized as an industry test methodology. This paper will investigate the challenges associated with creating such a channel model and extracting a performance metric from the test results, and will discuss the progress to date.

II. CREATING A DYNAMIC CHANNEL

To create a dynamic channel model that reflects the real-world experience, we must first look to the method carriers commonly use to evaluate their networks with real devices, commonly known as "drive testing", where a standard route is driven with one or more reference devices to evaluate throughput performance, dropped calls, and the like. Before the advent of OTA testing for transmitter and receiver performance metrics like total radiated power (TRP) and total isotropic sensitivity (TIS), drive testing was commonly used to qualify new user equipment before deploying them on the network. For some time now, channel sounding and other modeling tools have been used to create simulated virtual OTA environments that replicate, or at least approximate, some real-world scenarios without the need to perform physical drive testing.

While the idea of virtual drive testing is not new, standardizing on a model that will potentially impact the design of all cell phones and other user equipment deployed in North America and possibly around the world is not something to be taken lightly. Choosing a particular route through a particular city could bias the model towards a condition that may not exist in other areas or on other operators' networks. Other practical considerations also come into play. The model should encompass a wide range of channel conditions to exercise the device across a range of operating levels. Ideally, the model will also be spatially diverse, embedding the effects of device orientation within the variation of the model, thereby eliminating the need to rotate the device and repeat the test in order to get an average performance across different orientations. On the other hand, test time considerations, including test cost and battery life, prevent the generation of an exhaustive collection of test conditions in one extremely long scenario. Likewise, while one proposed approach would be to progress the scenario from an "easy" channel condition to one progressively harder in order to be able to test the device to failure and have a linear progression similar to a typical throughput vs. power test, that only results in testing half of the behavior of the device and doesn't evaluate how well it recovers as the channel condition improves.

Even though a dynamic channel model has yet to be standardized, 3GPP has specified a set of clustered delay line (CDL) models suitable for 5G testing [4]. Thus, it is desirable that the dynamic model would still reflect the concepts encompassed by one or more of these models. That could potentially be accomplished by lumping these models together in one long model, sequentially testing each condition. However, that's not a very realistic scenario and would generally introduce discontinuities at the transition that could produce unexpected results. Better yet would be to simulate the condition where a device roams from one environment to another (i.e. driving from the highway into dense city streets) but that implies cellular handover from one base station to another, which is not part of the desired MIMO OTA test. So instead, the choice was made to incorporate the models as waypoints within the virtual environment, where the channel conditions change gradually from one waypoint to the next, while maintaining the link to the same base station. This eliminates the roaming decision point that would normally exist when the DUT decides that one channel is better than the other, but otherwise exercises the device through each channel model in turn.

In real life mobile radio, the propagation channel is dynamic. The multi-path effect with fast fading is present, as well as gradual changes of the propagation angles, polarizations, and delays, along with potentially abrupt transitions between line-of-sight (LOS) and non-line-of-sight (NLOS) conditions or other shadowing effects. Conversely, in the prior stationary channel models, the DUT was still moving and experiencing fast fading channels, but the propagation environment did not change at all.

For dynamic radio channel conditions, large scale channel characteristics, such as angular power distribution, power delay profile, Doppler power spectrum, and LOS/NLOS condition, are varying over the emulation time. The path loss profile, user equipment (UE) speed profile, and UE orientation can also be defined to be dynamic. In a dynamic MPAC emulation, the channel model and the direction of highest power concentration can be rotated around the DUT by the fading emulator so that mechanical rotations of the DUT are not necessarily needed. At a minimum, the number of required test orientations can be greatly reduced.

The creation of dynamic models is covered in the following sub-sections. The modeling principle was originally described in [5] and then proposed to CTIA in [6], where a DUT route is defined by a number of waypoints as illustrated in Fig. 1. Each waypoint is assigned a different 3GPP CDL model, together with orientations, speed, and direction of travel of the UE. Finally, the fading channel coefficients are generated using the normal procedure defined in 3GPP TR 38.901 [4] for the interpolated propagation parameters. In addition, the fixed randomness concept introduced in [7], is applied for determining the initial phases of the polarization matrix to remove the dependency on random seed selection in channel coefficient generation.

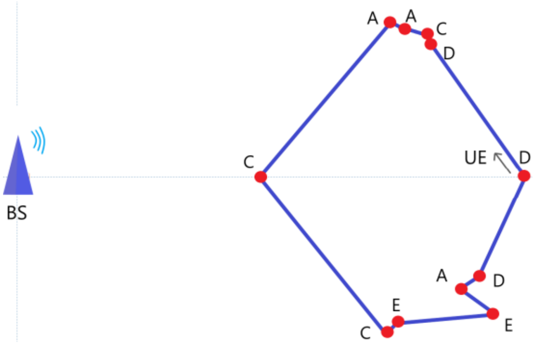

Fig. 1. Route of UMa model with 11 waypoints. (Modified from [6].)

A. *Defining multiple CDLs, LOS, NLOS, variable path loss*

Clustered delay line (CDL) models from [4] are allocated for each waypoint. Fig. 2 (top) shows CDL model names by letters A, C, D, and E on each route segment. Some of them are NLOS (A, C) and some are LOS (D, E) conditions. The distance dependent path loss is included in the model based on the simulated drive route shown in Fig. 1 taken from [6]. Fig. 3 illustrates the resulting fading profile for the urban macro (UMa) model. The shadow fading is kept at zero, i.e., additional shadowing is not introduced. It should be noted that transmit and receive antenna gains are not included in the channel gain curve of Fig. 3.

The LOS conditions are chosen for the farthest waypoints to reduce the overall path loss variation, although in most practical environments the closest link distances typically indicate LOS and the longest, NLOS conditions. However, very high dynamic variations of radiated signal are challenging to reconstruct in MPAC test environments. The resulting dynamic range of the average power (as opposed to the instantaneous fading profile) with this scenario is approximately 35 dB, which enables a practical test with a good range of varied SNR conditions with quick transitions reflecting behaviors seen in the real world. The LOS/NLOS condition is expressed in Fig. 2 (bottom) by the Ricean K-factor.

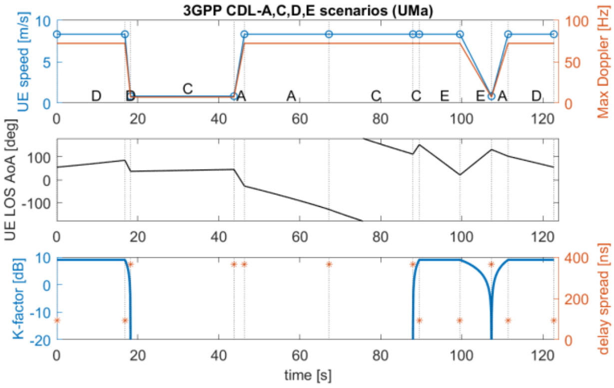

Fig. 2. UE speed and maximum Doppler frequency (top). LOS AoA as observed in the UE coordinate system (middle). Narrowband Ricean K-factor (bottom). Waypoints are shown by vertical dotted lines. Top figure contains the CDL model scenario label A,C,D,E on the time axis. Graphs are for the UMa scenario.

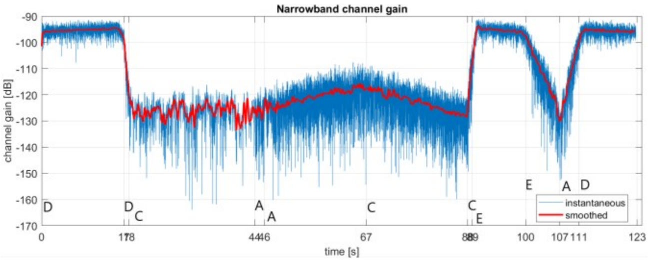

Fig. 3. Narrowband channel gain of the dynamic UMa channel model. “Smoothed” is a sliding averaged version of the “instantaneous” curve.

B. Interpolation

For continuous channel modeling, each parameter, such as UE speed, orientation, path delays, powers, Ricean K-factor, etc., must be interpolated between two successive waypoints, and linear interpolation is the simplest approach. Angles and angle spreads are interpolated in degree units, delays in nanoseconds, cluster powers and K-factors in linear units, and path losses and cross-polarization ratios in decibel units. The exception is the LOS direction, which is determined from linearly interpolated UE and base station (BS) coordinates.

Assume a parameter ε has value $\varepsilon\,(a)$ and $\varepsilon(b)$ at waypoint a and b, respectively. The linearly interpolated parameter value at time instant t is

$$\varepsilon(t) = \frac{\varepsilon(a)(T_{ab}-t)+\varepsilon(b)t}{T_{ab}}, \tag{1}$$

where T_{ab} is the total time from waypoint a to b in seconds, such that $t = 0$ at waypoint a and $t = T_{ab}$ at waypoint b.

Different waypoints may have different number of clusters. Assume waypoint a has N and b has $N + 1$ clusters. For cluster power interpolation the power of non-existing cluster $N + 1$ in waypoint a is set to $P_{N+1}(a) = -100$ dB and the power ramp is interpolated between a and b as defined by the previous equation. In LOS condition, the power of the LOS ray is determined by the Ricean K-factor. Transitions between LOS and NLOS conditions are handled by defining the power of the LOS ray to -100 dB for NLOS waypoints. For other parameters, the following rule for void clusters is applied. Parameter $\varepsilon(w, n)$ denotes the parameter value of cluster n at waypoint w. If cluster $(w - 1, n)$ is void and (w, n) is not, then $\varepsilon(w - 1, n) = \varepsilon(w, n)$, i.e. the value of the next waypoint is copied to the previous. The same applies if $(w + 1, n)$ is void and (w, n) is not, then $\varepsilon(w + 1, n) = \varepsilon(w, n)$.

C. Creating a drive route, DoT, velocity, AoA, etc

The basic geometry for the drive route is defined in Fig. 1. Both the BS and UE waypoints have specific coordinates with linear paths between them defining the route. The LOS direction at each point along the route is defined by the route coordinates relative to the BS coordinates. Direction of travel (DoT) is determined by the velocity vector that points always from the previous to the next waypoint on a route segment. The DUT is oriented with respect to the DoT, hence its orientation in relation to the LOS direction evolves continuously along the route. As the UE drives a full circuit, the relative LOS direction spins a full 360°. This is illustrated in Fig. 2 (middle).

UE velocity is set variant between 3 and 30 km/h as depicted in Fig. 2 (top). There are route segments with constant speed and shorter segments with constant acceleration or deceleration.

III. SYSTEM CONSIDERATIONS

This approach brings some new challenges to the design of the MIMO OTA test system. The concerns about device size and higher frequencies impose the same sort of design constraints as for the 3GPP approach, necessitating a higher probe density in order to maintain the required spatial correlation across expected antenna separation distances. However, the dynamic nature of the AoA information precludes any thought of optimizing probe placement based on the channel model. Thus, a uniform array will generally be required, especially if we want to avoid the need to rotate the DUT during the test.

The disparate performance metrics chosen by CTIA and 3GPP for LTE testing have always imposed different requirements on the dynamic range of the test system. For CTIA's SIR based metric, relatively high gain, high power amplification is required to ensure a high SNR at the DUT so that the resulting SINR at the DUT is approximately equal to the desired SIR. Conversely, the platform noise limited receiver sensitivity test used by 3GPP requires a comparatively low gain, low noise amplification to overcome OTA path losses but still allow generating a high system related SNR when the signal at the DUT is near its platform noise level. In other words, the noise level due to the system must be much lower than that of the DUT as the signal approaches the receiver sensitivity level.

The variability of the dynamic channel model, coupled with the link adaptation that allows the DUT to move from complex rank and modulations that require high SNR to low order settings that operate with a very low SNR, implies the need for a significant amount of dynamic range in the MIMO OTA system. To make matters worse, there is still an interest in the possibility of embedding intentional interferers into the channel model so that at certain points in the test, the DUT performance may be SIR limited rather than platform noise limited. Thus, the system SNR requirements may be considerably more stringent than those for the two cases defined above.

Fig. 3 illustrates the dynamic range required just to accommodate the fading of the proposed channel model. If we clip the few deepest nulls, we could assume a nominal 70 dB of dynamic range required just to represent the fading. On top of that we have to add headroom to accurately represent the most complicated 5G modulation and coding scheme. Nominally we can assume that a 12 dB crest factor is sufficient to cover the peak-to-average ratio (PAR) of the modulation, extending the dynamic range to at least 82 dB. A 14-bit DAC covers that dynamic range, but that doesn't address the need to still have a reasonably accurate modulated signal regardless of the output level. That would imply needing even more bits to minimize any digital error in the output signal. Instead, what is traditionally done with the stationary models, where the average power of a particular port may be considerably lower than another, is to decrease the analog gain proportional to the desired average power and then increase the digital gain to maximize the DAC dynamic range on every port (Fig. 4). The challenge now is that the average power on every port is dynamic and changes throughout the emulation scenario. Thus, in order to play this trick of maximizing the dynamic range, the channel emulator must be able to adjust the analog gain in real time as the model progresses.

Not only does the channel emulator need sufficient dynamic range to cover the model, but we need to be able to reproduce that dynamic range at a desired target signal level within the test volume. Even if we assume the SNR and dynamic range at the output of the channel emulator are sufficient to create the desired behavior if fed directly into a receiver, we still have to deal with the frequency dependent path losses inherent in an OTA test system. This generally requires amplification, but unfortunately, one is unlikely to find a broadband amplifier that can just exactly cancel out the system path loss. Commonly, such as for the 3GPP receiver sensitivity search, the output power control of the channel emulator is used to adjust the target signal level in the test volume. However, even if the amplifier does not add any additional noise to the system, reducing the output power of the channel emulator lowers the signals closer to its own noise floor, reducing the system SNR in the test volume. Likewise, not having enough amplification places the signal too close to the platform noise floor of the DUT. Fig. 5 illustrates these scenarios as well as the impact of not enough system SNR and dynamic range at the DUT. Ideally, power control for tuning the signal level in the test volume would occur after the last gain stage, or as part of a low noise variable gain amplifier.

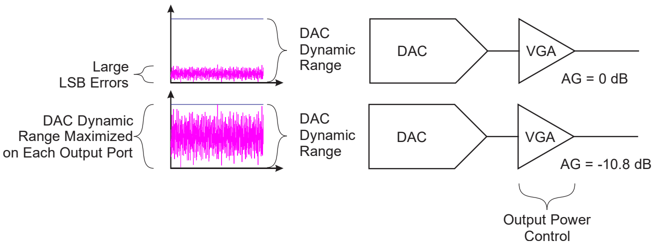

Fig. 4. Maximizing DAC dynamic range using analog gain control.

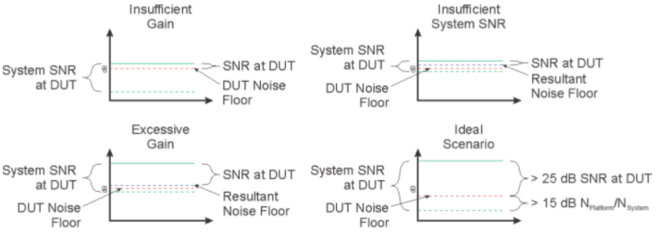

Fig. 5. Impact of system gains/losses on the available dynamic range and noise floor at the DUT.

IV. PERFORMANCE METRIC

The dynamic channel model replays a varying set of channel conditions that will be observed by the UE to emulate a virtual drive test. This produces some new challenges in determining a suitable performance metric, preferably a single value to enable comparing devices.

Average or inverse average power associated with a target mean throughput over a specified period of fading, averaged over a range of orientation angles, was used as the metric with stationary channel models. This requires a downlink power or SIR based receiver sensitivity search at each angle, varying the output of the channel emulator. However, this is not a feasible figure of merit with dynamic channel models since it ignores the variability of the radio conditions and the capability to adapt to them. A time variant throughput would be a potential performance metric, but fast variations, potentially due to random fast fading, makes it hard to condense into a single value. Good performance in "easy" segments of the channel model would dominate the average throughput over more nuanced performance in difficult regions. A cumulative distribution function (CDF) of throughput, collected from all throughput samples along the route, characterizes the variability of DUT performance in a single curve, removing the time dependent variation of the original test data. This provides a simple visual comparison of device behavior, while selecting a target probability level (e.g. what's the throughput this device reaches at least 50% of the time?) produces a single metric for easy device comparison. One weakness of the single point extraction from the CDF is that it misses the difference between devices that have significantly different spreads in their performance. For example, which device is better? One that varies evenly between 0 and 100 MBps performance or one that always has 50 MBps? The second device gives the user an acceptable guaranteed level of performance, while the first one would guarantee an annoyed user at least part of the time. One potential solution to this would be to take a few percentiles across the throughput CDF and use them as the performance metric.

Fig. 6 shows a CDF curve extracted from an example measurement using the present dynamic UMa channel model. The median, i.e., 50th-percentile, as well as 10th- and 90th-percentiles are marked in the plot. These three percentiles characterize the range of performance between nearly the best and worst throughput as well as the average performance along the course of dynamic channel model. A weighted combination of these percentages could be used to achieve a single value that incorporates the spread in performance as well as the average for comparisons between devices.

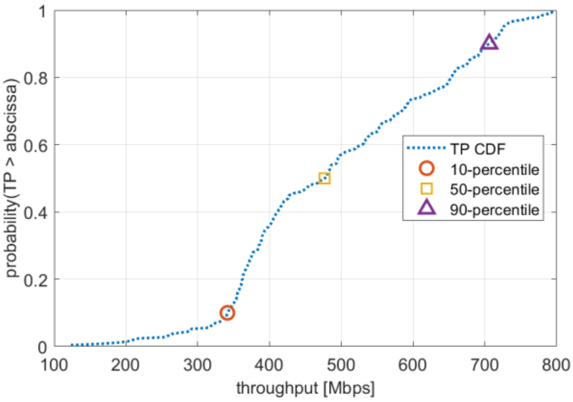

Fig. 6. CDF of measured throughput on the UMa route.

V. SUMMARY

The traditional spatial channel models and MIMO OTA test methodologies used for LTE provide limited information about the real behaviors of the device in the real world. At best they reflect the spatial correlation behavior of the embedded antennas, which is useful from a design research and development perspective, but is of limited use to wireless carriers for predicting the end user experience. For 5G FR1testing, the CTIA is pursuing a dynamic spatial channel model that provides a wide range of channel conditions to evaluate the corresponding range of device behaviors as it is allowed to adapt freely to the channel conditions. By creating a set of waypoints along a closed path, and assigning one of each of the 3GPP CDL models to those various waypoints, it is possible to create a variable model that encompasses all of the different test conditions defined by 3GPP and provides a 360° evaluation of the device performance without the need to rotate the device and repeat the test at multiple angles.

There are still technical challenges to be addressed due to the overall dynamic range of the channel model and the need to produce a target range of power levels within the test volume. The system must achieve the desired levels while ensuring that the SNR at the DUT is dominated by the noise floor of the DUT.

The dynamic nature of the model already includes all of the desired level variation to which the DUT will be exposed. There is no receiver sensitivity search process like is currently used for LTE or 3GPP 5G. Thus, a receiver sensitivity power level/SIR at a target throughput level is not a possible outcome of this sort of test. Instead, a CDF can be used to summarize the range of behaviors experienced throughout the circuit of the modeled path. By extracting a low, mid, and high percentile from the CDF, the effective performance spread can be evaluated in addition to the average performance. A weighted combination of those terms could then produce a single metric that balances average performance and range of performance. Such a weighting is yet to be determined

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REFERENCES

[1] Foegelle, M.D., "OTA Performance Testing of Wireless Devices with Multiple Antennas," Antenna Measurement Techniques Association (AMTA 2006), PID 524/A06-001.

[2] Foegelle, M.D., "Systems and Methods for Over the Air Performance Testing of Wireless Devices with Multiple Antennas," United States Patent 8,331,869 B2, December 11, 2012.

[3] TS 38.151, NR; Multiple Input Multiple Output (MIMO) Over-the-Air (OTA) performance requirements for NR UEs (Release 17), V0.5.0, August 2021.

[4] TR 38.901, Study on channel model for frequencies from 0.5 to 100 GHz, V16.1.0, Dec 2019.

[5] L. Hentilä, P. Kyösti and P. Heino, "Evaluation of beam forming and multi antenna techniques in non-stationary propagation scenarios with HW emulator," 2012 International ITG Workshop on Smart Antennas (WSA), Dresden, 2012, pp. 347-351

[6] T. Hertel, P. Kyösti, J. Kyröläinen, "On dynamic channel models for NR FR1 MIMO," MOSG210203R3 contribution to the CTIA MIMO OTA Subgroup, Keysight Technologies, May 2021.

[7] TR 38.827, Study on radiated metrics and test methodology for the verification of multi-antenna reception performance of NR User Equipment (UE), V16.2.0, March 2021.